PROGRESS REPORT OF FY 2000 ACTIVITIES: The Application of Kalman filtering to derive water vapor profiles from combined ground-based sensors: Raman Lidar, Microwave radiometers, GPS, and radiosondes.
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SCIENTIFIC GOALS OF RESEARCH

Kalman Filtering is a very general method to derive meteorological quantities from an combination of observations and models. Previously, the investigators have delivered to ARM a documented algorithm, to derive water vapor profiles from combined remote sensor measurements of water vapor radiometers, cloud-base ceilometers, and radio acoustic sounding systems (RASS). With the expanded deployment of a Raman lidar at the CART Central Facility, high quality, high vertical-resolution, water vapor profiles will be provided during nighttime clear conditions, and during clear daytime conditions, to somewhat lower altitudes. During clouds, the Raman profiles will extend from the surface to cloud base. The object of this effort is to use Kalman Filtering, previously applied to the combination of nighttime Raman lidar and microwave radiometer data, to derive high-quality water vapor profiles, during non-precipitating conditions, from data routinely available at the CART site. To combine data by Kalman filtering, it is necessary to know the error characteristics of each data source and to eliminate, as far as possible, sources of internal inconsistency between the data. The input data for our Kalman algorithm will include: (a) mixing ratio profiles from the ARM Raman lidar, (b) precipitable water vapor (PWV) from the ARM microwave radiometer (MWR) (c) PWV from the Global Positioning System (GPS) that is operated by the National Weather Service at Lamont, Oklahoma, and (d) aisala type radiosondes that are operated on the Balloon Borne Sounding System (BBSS) at the Southern Great Plains CART Central Facility. To achieve the required internal consistency of water vapor data, we are regarding the ARM MWR as an absolute standard, using a generalized tipcal method as a diagnostic tool for this instrument, and will include in our algorithms the most recent clear and cloudy radiative transfer equation (RTE) models. Both the tipcal method and the RTE models will be included in the Kalman Filter Algorithm.

ACCOMPLISHMENTS

- Development and open literature publication of tipcal diagnostics program for the ARM MWR. This program can test for atmospheric or instrumental asymmetries, in the angular scans of the MWR, as well as give a real time measure of the overall quality of the scan. This software has been recently transferred to ARM infrastructure.

- Development of improved microwave radiative transfer equation (RTE)software that incorporates recently developed absorption algorithms for both clear and cloudy atmospheres. This software has been recently transferred to ARM infrastructure.

- Applications of tipcal diagnostics program and the RTE software to data sets from the NSA/AAO Winter Radiometric Experiment and the Nauru'99 MWR data from ARCS2 instruments.

- SHEBA MWR reanalysis. We evaluated the role of both clear and cloudy absorption algorithms in the retrieval of both Precipitable Water Vapor and Integrated Cloud Liquid. Differences in retrieved PWV and ICL between original ARM and ETL algorithms for low amounts of vapor and for temperatures below –10°C were substantial.

PROGRESS AND ACCOMPLISHMENTS DURING LAST TWELVE MONTHS

(1) DEVELOPMENT OF THE TIPCAL DIAGNOSTICS PROGRAM

The tipping calibration method has been an important calibration technique for ground-based microwave radiometers that measure atmospheric emission at low optical depths**.** The method calibrates a radiometer system using data taken by the radiometer at two or more viewing angles in the atmosphere. In this method, the relationship between measured brightness temperature and atmospheric opacity is used as a constraint for deriving the system calibration response. Because this method couples the system with the radiative transfer theory and atmospheric conditions, evaluations of its performance have been difficult. In our work (Han and Westwater 2000), first a data-simulation approach was taken to isolate and analyze those influential factors in the calibration process, and effective techniques are developed to reduce calibration uncertainties. Then, these techniques were applied to experimental data that were taken during the 1998 Water Vapor Intensive Operating Period. The influential factors include radiometer antenna beam width, radiometer pointing error, mean radiating temperature error, and horizontal inhomogeneity in the atmosphere, as well as some other factors. It was demonstrated that calibration uncertainties from these error sources can be large and unacceptable. Fortunately, it was found that by using the techniques reported here, the calibration uncertainties can be largely reduced or avoided. With the suggested corrections, the tipping calibration method can provide absolute accuracy about or better than 0.5 K. The tipcal program was implemented as a flexible executable computer code that has been implemented on several PC platforms and in several languages, including IDL and MATLAB. The tipcal algorithms use the standard ARM NETCDF format for input data from the ARM MWR and were implemented on ARM computers on June 2000.

(2) DEVELOPMENT OF IMPROVED MICROWAVE RTE PROGRAMS

Microwave radiometric retrievals of Precipitable Water Vapor (PWV) and Integrated Cloud Liquid (ICL) as well as profiles of temperature, water vapor, and cloud liquid, all require models of the dependence of absorption and emission. We have improved the original radiative transfer equation algorithms (Schroeder and Westwater 1993) that were delivered to ARM by testing clear emission algorithms from Liebe (1987), Liebe (1993), and Rosenkranz (1998), as well as cloud liquid absorption algorithms from Grant et al. (1957), Rosenberg (1971), and Liebe et al. (1991). We delivered to ARM models that we recommend, namely Rosenkranz (1998) and Liebe et al. (1991).

(3) APPLICATION OF THE TIPCAL ALGORITHMS TO THE NSA/AAO ARCTIC WINTER RADIOMETRIC EXPERIMENT

The Millimeter-wave Radiometric (MMWR)-Arctic experiment was conducted in March 1999 at the North Slope of Alaska/Adjacent Arctic Ocean Cloud and Radiation Testbed (NSA/AAO CART) site. During the experiment, the NASA Goddard Space Flight Center and the NOAA Environmental Technology Laboratory (ETL) deployed four microwave radiometer systems with a total of 24 radiometric channels ranging in frequency from 20.6 GHz to 340 GHz. One of the objectives of this experiment was to evaluate, during extreme cold conditions, the performance of the ARM dual-channel (23.8 and 31.4 GHz) microwave radiometer (MWR) that is routinely operated at the CART site to derive precipitable water vapor (PWV) and cloud liquid water.

However, initial comparisons of the 183 GHz with the original archived ARM MWR brightness temperature Tb measurements showed substantial differences. These differences were the result of a software attempt to compensate for improper temperature regulation at low temperatures. These data were re-calibrated by ETL using an instantaneous calibration factor. Fig. 1 shows the original- and ETL-corrected MWR data. It was evident by comparison with both NASA and ETL radiometric data that the use of the instantaneous tipcal method dramatically improved ARM MWR retrievals.

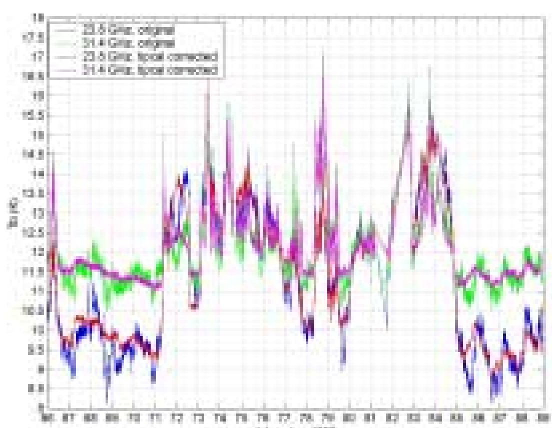

Fig. 1. Comparison of ARM MWR Tb measurements during the NSA/AAO Arctic Winter Radiometer Experiment. The green and blue line are from the original ARM archive; the magenta and red are from the ETL re-calibrated data. PI's: Y. Han and E. Westwater (CIRES, Univ. of Colo./NOAA-ETL), 2000.

(4) APPLICATION OF THE TIPCAL ALGORITHMS TO ARM MICROWAVE RADIOMETERS DURING NAURU' 99

Initial comparisons between ARM MWR data and brightness temperatures calculated from ARCS2 radiosondes showed that there were significant differences, at times reaching 12 K. Many of our comparisons with other data rely on the accuracy and consistency of the ARCS-2 MWR, the quality of its calibration was crucial. During this experiment, the radiometer was run in a nearly continuous tipcal mode. When the sky conditions were favorable, as determined by symmetry of radiometry scans, the radiometer continued scanning at angles corresponding to the air masses 1, 1.5, 2.0, and 2.5 (elevation angles of 90, 41.8, 30, and 23.6 degrees). We applied the ETL calibration method (Han and Westwater, 2000) to the tipcal data, and showed that the ARM radiometer was in excellent calibration. Our results, requiring beam width and angular-dependent mean radiating temperatures, use equivalent zenith brightness temperatures as a measure of calibration quality. Rms departures of this measure were frequently better than 0.2 K, indicating a high degree of atmospheric stratification and antenna beam symmetry. Examples of tipcal data taken during Nauru'99 data are shown in Fig. 2. Such data may be immediately used for quality control.

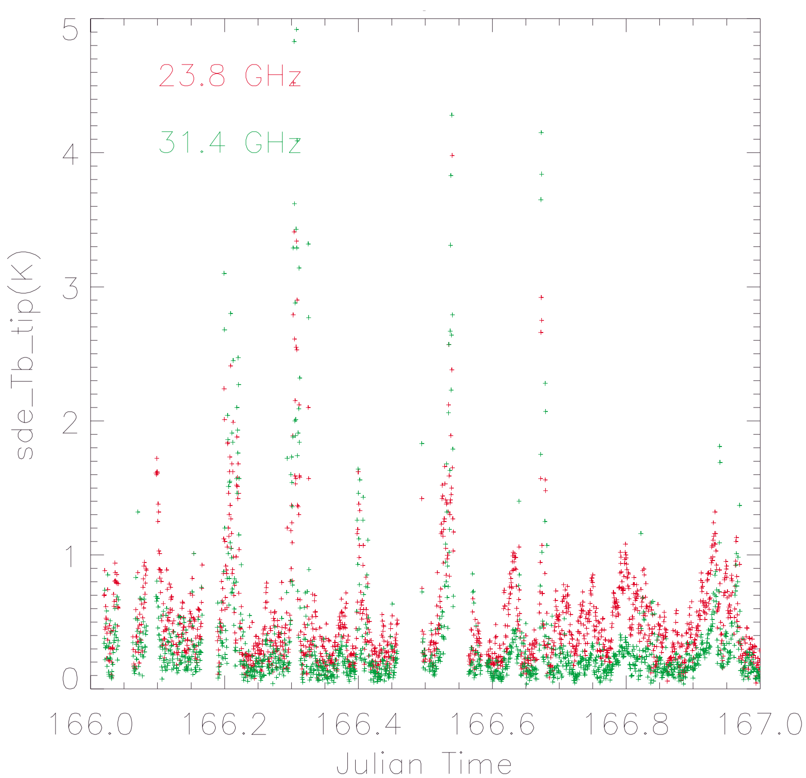

Fig. 2. Standard deviation of equivalent zenith Tb's from ARM MWR at ARCS2 during Nauru'99. PI: E. Westwater (CIRES). 2000.

(5) REANALYSIS OF ARM MWR DATA TAKEN DURING SHEBA

Because of concerns with certain aspects of the ARM MWR during SHEBA, we did a complete re-analysis of a 4-month segment of data from April-July, 1998. This analysis was preceded by a theoretical study of three contemporary clear sky absorption algorithms and three commonly used cloud liquid absorption algorithms. The reanalysis of SHEBA data entailed a comparison of various cloud liquid and water vapor retrieval algorithms, both statistical and physical, as well as the use of radar, ceilometer, and radiosonde data in cloud liquid retrievals. Basically, the original ARM retrievals of cloud liquid were about 30% higher than the new ones of ETL, but during cold conditions of less than –10°C, the original retrievals were higher by a factor of two. An example of the original vs. ETL-corrected cloud liquid retrievals are shown in Fig. 3. The results of this analysis are being prepared for a journal paper.

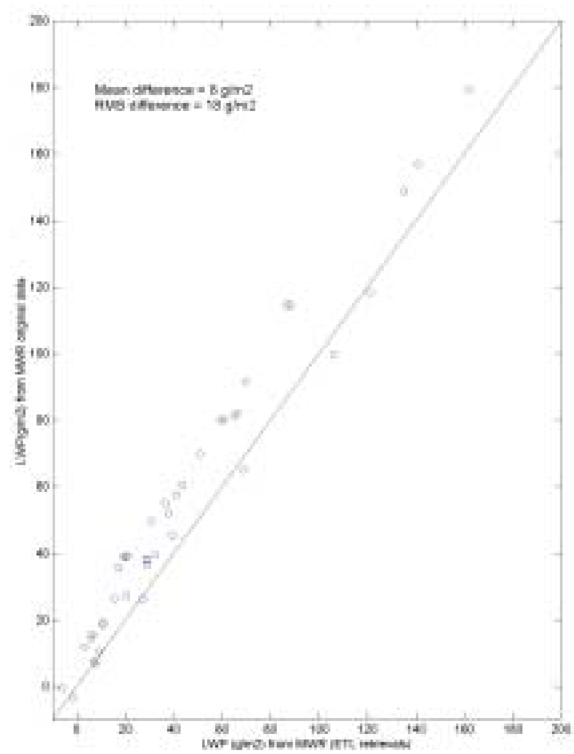

Fig. 3. Scatter plot of original ARM MWR retrievals of integrated cloud liquid vs. ETL physical retrievals. Rosenkranz (1998) and Liebe et al. (1991) models of clear and cloudy absorption are used in the retrievals. PI's: Y. Han and E. Westwater (CIRES/Univ. of Colo./NOAA-ETL). 2000.

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CONFERENCE PROCEEDINGS AND EXTENDED ABSTRACTS

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PROPOSED WORK FOR FY 2001 ACTIVITIES: THE APPLICATION OF KALMAN FILTERING TO DERIVE WATER VAPOR PROFILES FROM COMBINED GROUND-BASED SENSORS: RAMAN LIDAR, MICROWAVE RADIOMETERS, GPS, AND RADIOSONDES. (INTERAGENCY AGREEMENT NO. DE-AI03-97ER62343)

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(1) RE-ANALYSIS OF SHEBA MWR DATA

(A) ETL proposes to re-analyze the complete data set of ARM MWR data taken during SHEBA. This re-analysis includes retrieval of Precipitable Water Vapor and Integrated Cloud Liquid by a variety of physical and statistical retrieval algorithms. Lidar, cloud radar, and radiosondes, will be used the analysis.

(B) Publication of results in the open literature.

(2) DEVELOPMENT OF A KALMAN FILTER CALIBRATION ALGORITHM FOR THE ARM MWR TIPCAL DATA

(A) The generalized tipcal program has as its output standard deviations of equivalent zenith brightness temperatures for each tipcal. These standard deviations vary due to changing atmospheric conditions and instrumental drifts. By appropriate application of Kalman Filtering, optimized averages of tipcal data could be generated for the ARM MWR.

(B) Publication of results in the open literature.

(3) APPLICATION OF KALMAN FILTERING TO THE COMBINATION OF DATA FROM ARM INSTRUMENTS TO DERIVE WATER VAPOR PROFILES

(A) With the development of the tipcal diagnostic program, and the improvement in forward modeling algorithms for microwave radiative transfer, the ARM MWR can be used as an absolute standard for PWV measurements. Using this standard, the ARM Raman lidar, water vapor soundings from the BBSS, and GPS soundings of PWV, can all be converted to quantities that are internally consistent. All of these internally consistent data can now be combined with ARM active measurements of cloud height and perhaps thickness to provide high quality vertical profiles of water vapor.

(B) Transfer to ARM of the KF programs.

(C) Publication of results in the open literature.